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A question of timing: spatio-temporal structure and mechanisms of early agriculture expansion in West Africa

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A B S T R A C T

Although understanding the emergence of agriculture in West Africa has recently benefited from major advances, the reasons for its fast diffusion south of the Sahara remain to be explained. We propose here a reconstruction of African agriculture expansion built from a spatialization of available archaeological data and associated radiocarbon dates. With this approach, we can show that the initial spread of food production occurred with some specific rhythms. From this structure, we discuss the potential underlying processes. Our work suggests that the spread of agriculture in West Africa cannot be explained by a simple response to an abrupt environmental change at the beginning of the Late Holocene, but rather by a combined climate-culture mechanism. In addition, cord-wrapped roulette-impressed pottery appears to be a good indicator of the expansion of agro-pastoralist populations in Sub-Saharan regions. Our results are also consistent with the assumption of a monophyletic origin of domestic pearl millet in south-western Sahara and strengthen the idea that the first cultivators were Saharan pastoralists.
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1. Introduction

In recent decades, knowledge about the emergence of food production in Africa has improved considerably. Sub-Saharan African early agriculture corresponds to the beginning of pearl millet cultivation. Domesticated pearl millet (*Pennisetum glaucum*) first appeared at the Sahara-Sahel border during the second part of the 3rd millennium cal BC and then spread into the Sahelo-Sudanian belt (Amblard and Pernès, 1989; Neumann et al., 1996; Klee et al., 2000; D'Andrea et al., 2001; Zach and Klee, 2003; Klee et al., 2004; Ozainne et al., 2009; Manning et al., 2011; Eichhorn and Neumann, 2013). It has been proposed that indigenous African agriculture was first developed by Saharan pastoralists (Manning, 2010). The crop was probably integrated as a secondary livelihood within a mobile seasonal lifestyle, enabling better predictability of resources and greater subsistence safety in the context of increasing aridity (Marshall and Hildebrand, 2002; Neumann, 2003). However, the precise mechanisms of its spread as well as its relationships with the major climatic and cultural developments south of the Sahara during the Late Holocene remain to be elucidated. The main issue is to uncover the causes of the apparent rapid expansion of plant cultivation in the Sahelo-Sudanian belt.

Archaeological evidence for human occupation during the Early and Middle Holocene is scarce in Sub-Saharan West Africa, while data younger than 2500 cal BC are much more numerous. This phenomenon is commonly regarded as the consequence of southward migration following major climate and environment changes in the Sahara from the end of the Middle Holocene onwards, although the validation of such a model in West Africa would require more fundamental data. Recent research suggests that the expansion of agriculture may be related to a particular cultural

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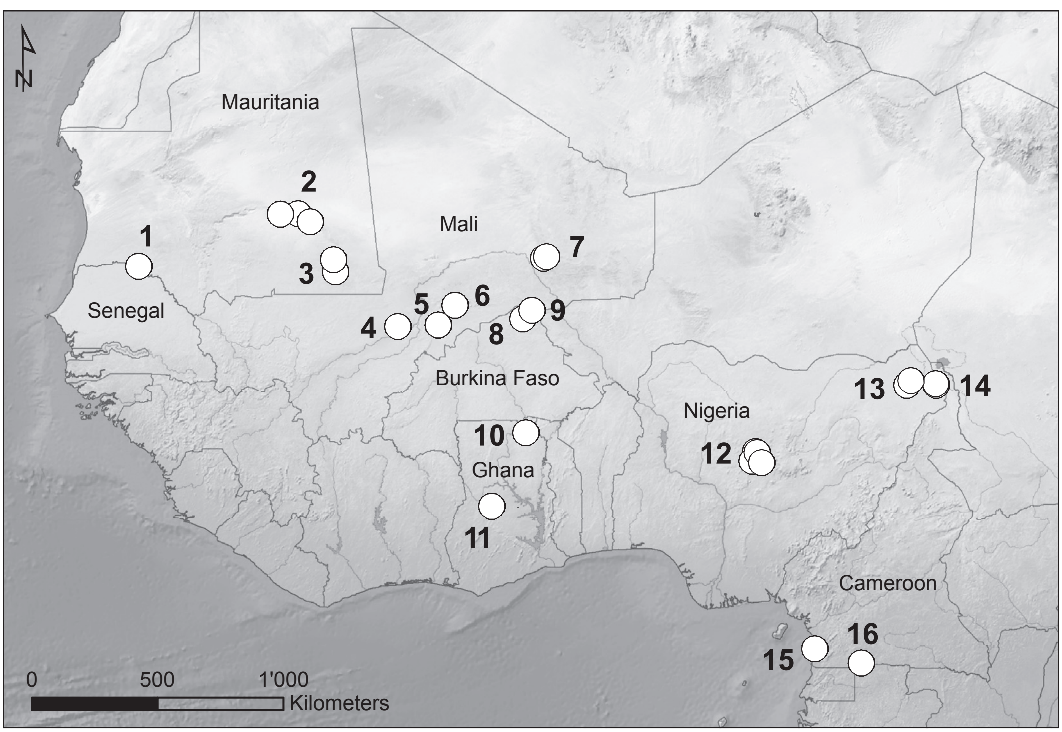
stream in the Sahel-Sudan area during the second millennium cal BC (Ozainne, 2013, 2014). This pattern is mainly visible through a coherent group of archaeological entities, principally characterized by vessels with narrow openings decorated with rolled impressions of particular cord-wrapped roulettes. Understanding the expansion of agriculture and its likely association with stylistic characteristics of pottery in Sub-Saharan zones requires further analysis of hitherto underexploited chronological data.

In this paper, we design a spatio-temporal framework of the agriculture expansion in West Africa based on a spatialization of the associated radiocarbon data. From the results, we discuss the cultural mechanisms of this important socio-economic change and the possible relationships between the rise in food production and the main environmental changes of the Late Holocene in West Africa.

2. Data and methods

2.1. Spatio-temporal analysis of archaeological data

In order to assess the spatio-temporal structure of early agriculture in West Africa, combined methods were used to plot and map the chronological information linked with Late Holocene occupation and pearl millet cultivation in West Africa, with an emphasis on the 2600–200 cal BC period. This includes the first phase of agricultural development between 2500 and 800 cal BC and the beginning of agricultural intensification and diversification that started with the West African Early Iron Age from ca. 800 cal BC (Kahlheber and Neumann, 2007). Thus, a dataset of 376 radiocarbon dates, comprised in a broader interval between 5500 and 2000 BP, was analysed in order to assess the general chronology of occupations (Table S1). The dataset included a subset of 76 dates related to the expansion of agriculture, either direct dates on pearl millet caryopses or on ceramics with pearl millet remains or impressions, or dates made on other materials coming from well-studied archaeological contexts in which pearl millet caryopses or ceramics with pearl millet impressions were discovered (Fig. 1). The single dated pearl millet grain discovered at Boase (Ghana; Fig. 1, n°11) was not considered as evidence of local agriculture, but rather as proof of trade among the different Kintampo communities (see Watson, 2010; Logan and D'Andrea, 2012). Its associated data were therefore not included in the calculations. Another subset of 141 dates is related to the development of pottery decorations made of rolled impressions obtained by using particular composite cord-wrapped roulettes with simple or multiple-core structures (Ozainne, 2010a, b; Ozainne, 2013). This decoration technique has



	Site/sites group	Country
1	Waladé	Senegal
2	Dhar Tichitt-Walata sites	Mauritania
3	Dhar Nema sites	Mauritania
4	Dia	Mali
5	Ounjougou	Mali
6	Windé Koroji	Mali
7	Lower Tilemsi Valley sites	Mali
8	Oursi	Burkina Faso
9	Tin-Akof	Burkina Faso
10	Birimi	Ghana
11	Boase sites	Ghana
12	Nok Culture sites	Nigeria
13	Gajiganna Culture sites	Nigeria
14	Kursakata, Mege	Nigeria
15	Bwambé Sommet	Cameroon
16	Abang Minko'o	Cameroon

Fig. 1. Sites with dated pearl millet finds. References in Table S1.

ancient origins and is documented from the Early-Middle Holocene in the Saharan zones (MacDonald and Manning, 2010; Garcea, 2013), but its earliest intensive use is recorded in the Lower Tilemsi Valley (Mali), in conjunction with the first evidence of pearl millet cultivation (Manning, 2011), and it is frequently represented in Sahelian and Sudanian archaeological sites from 2500 cal BC (Ozainne, 2013).

Chronological information was synthesized by summing probability distributions of calibrated radiocarbon dates. The use of summed calibrated probability distributions (often referred to as cumulative probability functions or CPFs) has recently become common in palaeoenvironmental and archaeological research, particularly to reconstruct prehistoric demographic trends (Gkiasta et al., 2003; Shennan and Edinborough, 2007; Riede, 2008; Smith et al., 2008; Collard et al., 2010; Hoffmann et al., 2008; Williams, 2012; Chiverrell et al., 2011). However, this method should be used carefully as it is linked to several important biases. Sampling biases are noteworthy, especially in relation to inter-site variation given that some regions and periods have clearly been more extensively studied (e.g. the emergence of agriculture in northern Mali or its development in the Lake Chad basin). The state of research may therefore have a considerable impact on cumulative curves. The increasing loss of archaeological information with age (or taphonomic loss) is also an issue (Williams, 2012). The most problematic bias probably comes from the calibration of radiocarbon measurements, as fluctuations in the atmospheric concentration of radiocarbon produce wiggles in the calibration curve. It appears, therefore, that the shape of a summed probability curve is a function of the calibration of radiocarbon ages (Chiverrell et al., 2011). Nevertheless, the use of CPFs is relevant here as our aim is not to identify and quantify demographic change but rather to assess the spatio-temporal structure of agricultural expansion in West Africa better.

All dates were converted to calendar ages at one-year precision using Oxcal 4.1 with the IntCal 09 calibration curve (Bronk Ramsey, 1995, 2008; Reimer et al., 2009). Following Collard et al. (2010), dates obtained from the same archaeological entities (which are coherent archaeological contexts, horizons or phases as defined from published studies) were first grouped (see Table S1 for groupings) and their calibrated curves were summed using Oxcal. The areas under the resulting summed curves were then normalized to one in order to control the variation in dating intensity, as some sites and entities have been intensively studied and are associated with a higher number of dates. Then, final cumulative

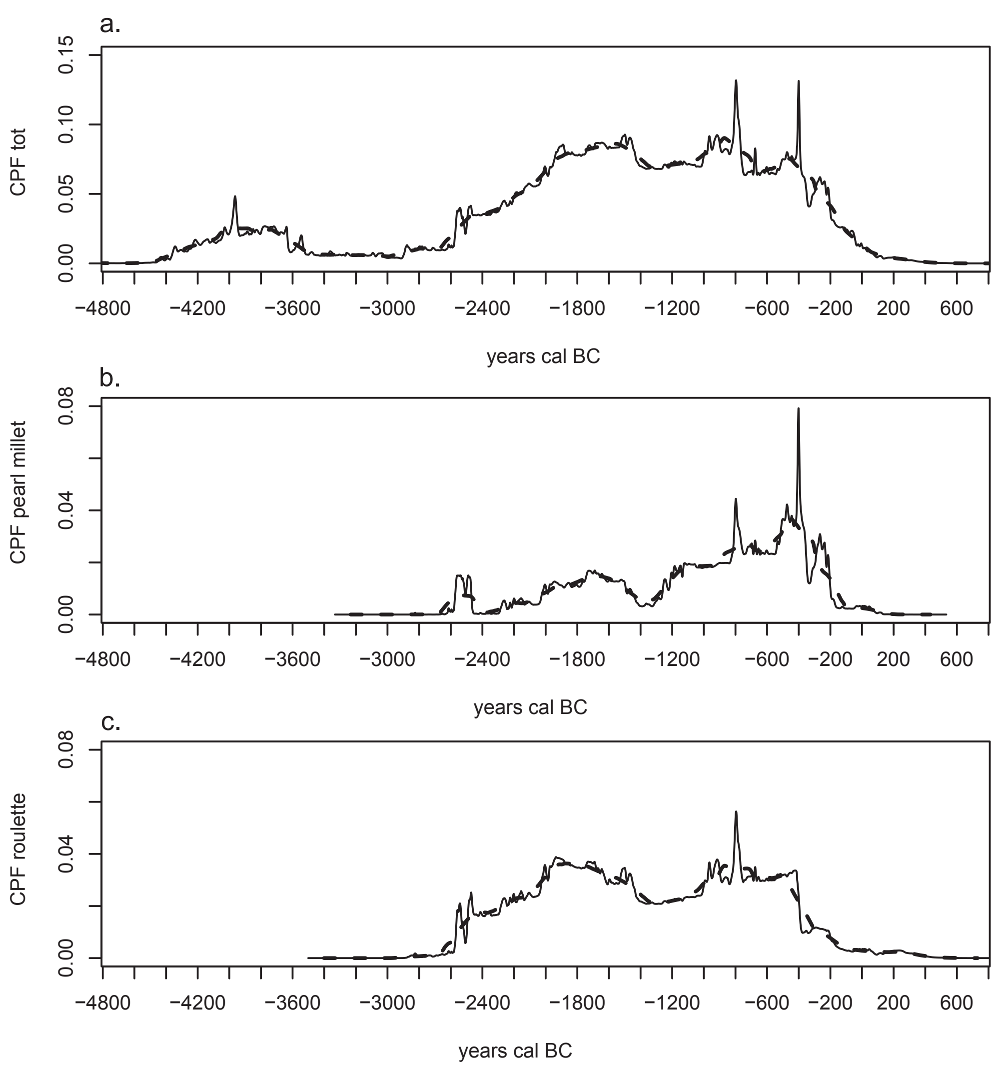


Fig. 2. Cumulative probability functions (CPF) of calibrated radiocarbon dates between 5500 and 2000 C14 years BP. a: Entire set of dates (see Table S1). b. Pearl millet related dates. c. Cord-wrapped roulette decorations related dates. Dashed lines correspond to the 200-years moving average smoothing (see text).

probability functions were plotted from the entire dataset and the two subsets of archaeological data (Fig. 2 a–c).

As stressed before, no method seems able to remove all the effects of the calibration curve on the CPFs (Chiverrell et al., 2011). Although this approach is useful for comparing the timings or intensity of archaeological developments, it is important to know its limitations before any interpretation. In particular, the distinct peaks of the agriculture curve at around 800 and 400 cal BC are strongly influenced by the "Iron Age plateau" of the calibration curve (Fig. 2b). In order to mitigate visually the effects of the calibration curve wiggles on the CPFs, and thus prevent any misleading interpretation of the major peaks produced, a 200-year moving average was added on the CPF curves of Fig. 2, in accordance with Shennan et al. (2013).

The CPFs were mapped by plotting bubble charts over the study area. The bubble sizes were calculated using the 200-year moving average smoothed CPFs. For this purpose, smoothed values of individual CPFs corresponding to each site were binned and summed for each time step. Spatial and temporal binning and calculations were performed using a series of R scripts and an Access relational database in which all calibrated probabilities at one-year precision were stored. Thus, every resulting map simply represents a spatial distribution of the curve information for the selected time intervals. In order to illustrate clearly and compare the spatio-temporal patterns of pearl millet and cord-wrapped roulette decorations, a constant 400-year step was arbitrarily set, starting at 2600 cal BC (Fig. 3). This cartographic sequencing also proved effective for the discussion as it enabled the main changes of the expansion sequence to be highlighted (see 3.1).

In order to quantify and compare the dispersal trends of roulette-impressed pottery and agriculture, standard distance values from the point subsets associated with each calendar year were also calculated and plotted (Fig. 4). Standard distance has long been considered an effective way to measure the dispersion of a population over a territory (Bachi, 1962). With the aim of taking into account the chronological information better, weighted standard distances (WSDs) were calculated. To this end, CPFs smoothed with a 200-year moving average were generated for each point and the probabilities corresponding to each year were used to weight the distances between the points and the mean centre corresponding to each year. To investigate the dispersal trends of roulette-impressed pottery and agriculture, linear regression models were run separately on each variable of these dependent variables, including "years" (calibrated BC) as a fixed factor. The square of the variable "years" was also included to consider potential non-linear trends in the relationship. Goodness-of-fit was estimated from the adjusted R squared. Separate linear models were chosen, given that pearl millet and WSD curves cannot be considered independent, because both time series were built from the CPFs and are affected by the variations of the calibration curve.

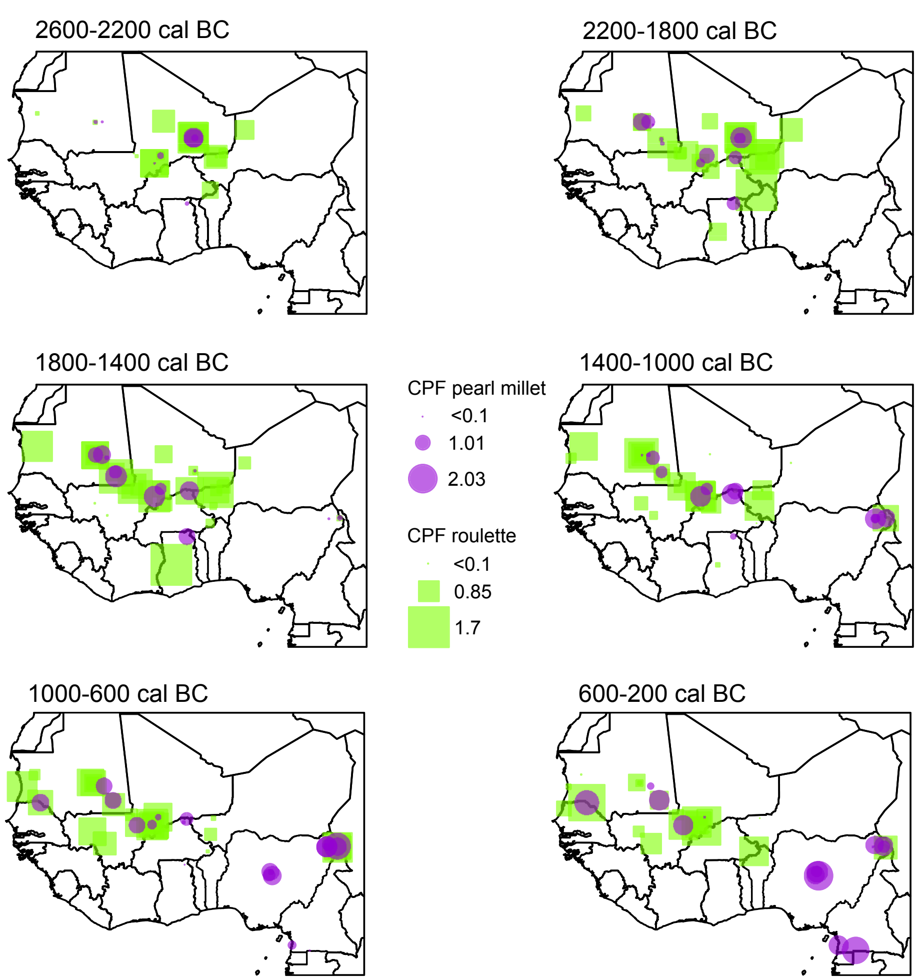


Fig. 3. CPFs mapping. As a visualization tool, the disks and squares do not represent actual surfaces, but the amount of chronological information at each point. Chart sizes were calculated from the 200-years moving average smoothed CPFs for each site and time binning, and plotted as disk or squares area values. Transparency of symbols does not have any numeric meaning but only serves to distinguish the superimposed dots on the maps.

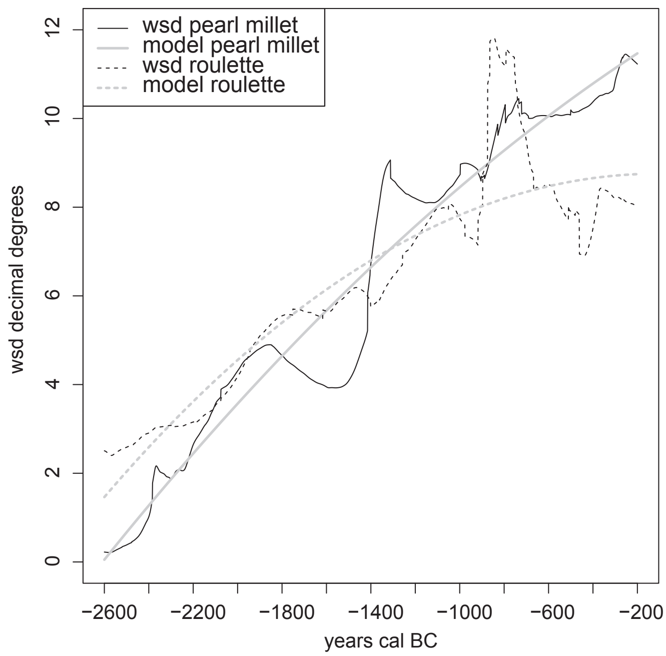


Fig. 4. Weighted standard-distance curves and models for pearl millet and cord-wrapped roulette decorations. Modelled WSD pearl millet $= -6.148{*}10^{-7}\text{year}^2 + 3.036{*}10^{-3}\text{year} + 12.10$. Modelled WSD roulette $= -1.176{*}10^{-6}\text{year}^2 - 2.587{*}10^{-4}\text{year} + 8.740$. See text for explanation.

Final CPFs and spatialization of calibrated radiocarbon dates as well as all statistical analyses were carried out through a series of R scripts (R Development Core Team, 2013). The CPFs and the standard distance curves were made using the plyr package (Wickham, 2011). Bubbles maps were plotted using the plyr and maptools (Lewin-Koh and Bivand, 2013) packages, with base maps made with Quantum GIS 1.8.0 (QGIS Development Team, 2013) and Natural Earth data.

2.2. Assessment of environmental transitions

Despite a recent increase in research on African Holocene climate changes, it remains difficult to compare the results of palaeoenvironmental and archaeological studies, especially as well-dated palaeoenvironmental data from Sub-Saharan zones of West Africa are scarce (Lézine et al., 2011). Many areas, such as the western part of the Sudanian belt, remain almost unknown, and associated age models rely on ancient dates with large uncertainties. Moreover, palaeoenvironmental archives often cover only a part of the period considered here, as the lacustrine, palustrine and fluvial records of the Saharan zone stop with the drying of the associated biophysical systems, while on more southern sites, records only started very recently (e.g. in the Niayes depression in Senegal; Lézine, 1989).

Proxies used to infer climatic and hydrological changes are quite diverse. They come from geomorphological studies of fluvial systems (e.g. Gumnior and Preusser, 2007; Lespez et al., 2011), geomorphological and sedimentological studies of lakes or swamps (e.g. Maley, 1981, 2010; Servant, 1983), diatoms and pollen (e.g. Gasse, 2002; Lézine et al., 2005, 2011; Salzmann et al., 2002) or, less frequently, they are based on multiple indicators (e.g. Waller et al., 2007; Kröpelin et al., 2008b). Furthermore, climatic transitions can be either abrupt or gradual, and it is sometimes difficult to interpret the beginning of arid periods. For instance, the phytolithic sequence of the Yamé valley in Mali (Garnier et al., 2013) indicates that the opening of the vegetation, correlated with a drying trend, started around 2600 cal BC, but the hydro-sedimentary data show that this trend intensified only from 1800 cal BC (Lespez et al., 2011). Finally, the environments of the different regions in the Sahara show variable and unsynchronized responses to climate change from the mid-Holocene onwards (Liu et al., 2007; Kröpelin et al., 2008a; b; Brovkin and Claussen, 2008), making it problematic to establish a unique scenario of climate-related population movements.

Despite these problems, a recent model for the development of the total humid surface in northern Africa between 10 N° and 28 N° during the Holocene (Lézine et al., 2011) offers an insight into the main climatic constraints that may have played a role in the expansion of agriculture. This study emphasizes a two-step general aridification pattern, with a “drying out of all Saharan water bodies at 4.5 kyr BP”, followed by an “increase in regional drought that caused the fragmentation of the humid sector” while the Sahel “underwent a short but clearly defined humid phase between 3.5 et 2.5 kyr BP” (Lézine et al., 2011). Although the time resolution of the latter study relies on a coarse 1000-year resolution (which is inevitable given the specific time and space scales it considers), the resulting humid surface variation curve (Lézine et al., 2011: Fig. 6) provides a valuable synthetic document, enabling a broad comparison with the rhythm of agriculture expansion and thus a discussion of its possible climatic mechanisms (Fig. 5a). On the other hand, this curve also prevents highlighting of local case studies and taking into account finer climatic variations, as environmental responses to this general pattern have clearly occurred more locally and rapidly and with irregular timings. In order to present more precisely the spatio-temporal variability of environmental changes in the area of agriculture expansion, and thus allow a better discussion of climate and culture interactions, we mapped the main drying thresholds that occurred between 2600 and 0 BC using a four-period binning (Fig. 6; Table S2).

3. Results and discussion

3.1. Overall structure and rhythm of the expansion of agriculture

Overall, the CPFs (Fig. 2), the CPF mappings and the WSD curves (Figs. 3 and 4) clearly show that agriculture expansion and the increase in the archaeological signal after 2600 cal BC in Sub-Saharan West Africa are synchronic. Some major transitions in the sequence rhythm are also visible at around 2200, 1400, and between 1000 and 800 cal BC (Figs. 2, 3 and 5).

Following the appearance of pearl millet cultivation, a first turning point may have occurred from around 2200 cal BC, as a rapid expansion of agriculture is documented in south-western Gourma and the Dogon Country in Mali and northern Burkina Faso, along the Dhars Tichitt-Walata in Mauritania, and in northern Ghana. A second important change is visible after 1400 cal BC, as pearl millet appeared in the Lake Chad Basin. Although the apparent slowdown of expansion between 2000 and 1400 cal BC may reflect a sample bias, given that some regions are poorly documented for this period (Fig. 3), this transition might reveal some change in the expansion mechanisms (see 3.2).

After 1000 cal BC, and especially from 800 cal BC, pearl millet appears in new areas and is attested in the Niger Inland Delta in Mali, in the Middle Senegal Valley, in central Nigeria and in southern Cameroon. Despite sampling and calibration effects, the increase in the pearl millet CPF during the first millennium cal BC corresponds to a real extension and amplification of agriculture practices, as shown by intensive archaeobotanical studies in the Lake Chad basin, which indicate that the number of pearl millet remains grew considerably from the Late Stone Age/Early Iron Age

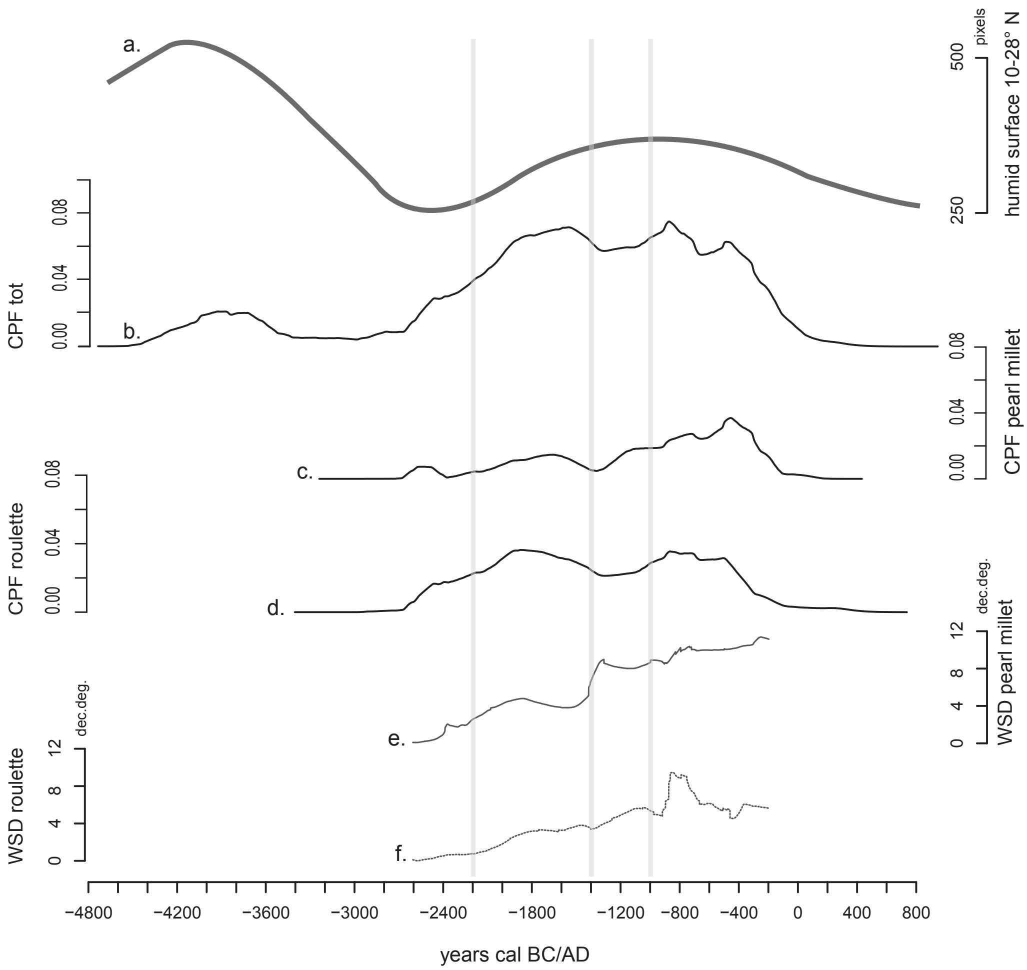


Fig. 5. a. Variation of humid surface in northern Africa, after Lézine et al. (2011). b, c, d: Smoothed CPFs of the complete dataset (see Table S1), pearl millet and cord-wrapped roulette decorations. e., f. WSDs of agriculture and cord-wrapped roulette decorations. Light grey shaded bars indicate the major thresholds of the sequence discussed in the text (see 3.1. and 3.2.).

transition, around the beginning of the 1st millennium cal BC (Klee et al., 2000, 2004; Zach and Klee, 2003).

3.2. Agriculture expansion and spread of roulette-decorated pottery

Analyses of weighted standard distances revealed a dispersal trend of roulette-impressed pottery, as a significant effect of "years" ($F_{1-2398} = 11858.22$, $P < 0.001$) and the square of this variable ($F_{1-2398} = 684.65$, $P < 0.001$) was detected. In the same way, a significant effect of "years" ($F_{1-2398} = 41115.09$, $P < 0.001$) and the square of this variable ($F_{1-2398} = 263.91$, $P < 0.001$) was found on the weighted standard distances of agriculture. The significant non-linear dispersal trends were supported by the adjusted R squared values assessed from the fit of roulette and agriculture WSDs, which reached 0.84 and 0.95, respectively. Fig. 4 shows the dispersal trends and suggests that roulette and agriculture WSDs exhibit two different strengths. However, further studies are needed to test for potential significance between these trends as they are both influenced by the calibration curve and can therefore not be regarded as independent. In future research, cross-correlation studies, including significance tests using confidence intervals calculated from simulated WSDs, should be carried out as such an approach was recently successfully developed to test for correlations between a demographic trend inferred from summed calibrated date probability distributions and different climate proxies (Shennan et al., 2013).

Although they cannot be considered significant evidence, the different strengths revealed by the expansion trends of pearl millet and roulette raise questions about the role of cultural processes in the diffusion of agriculture in West Africa. In fact, mapping of CPFs shows that the dispersion of cord-based roulette impressions in Sub-Saharan zones had apparently begun prior to that of domestic pearl millet and slightly preceded the arrival of agriculture during its first phase of expansion (Fig. 3). Although rouletted pottery is very ancient in the Sahara, this apparent spatio-temporal lag does not necessarily mean that roulette decoration techniques systematically spread southwards or emerged before agriculture at the beginning of the Late Holocene. It may rather reflect a pioneering component at the beginning of agriculture expansion, when mobile groups progressively tested pearl millet cultivation in new areas (see 3.3). Because cultivation was probably first developed as a secondary subsistence practice (Kahlheber and Neumann, 2007), it is likely that pioneering agricultural activities are hard to detect or may even remain archaeologically invisible, given that very small-scale cultivation evidence has a much weaker conservation potential than pottery. Furthermore, cord-based pottery decorations are possibly linked with an early pastoral context in southern Algeria (Messili et al., 2013), or even with a pre-pastoral one in Niger (Garcea, 2013). Hence, the overall association between cord-wrapped roulette decorations and the spread of agriculture tends to confirm that the first cultivators were pastoralists with Saharan origins. Our results therefore broadly suggest that agriculture

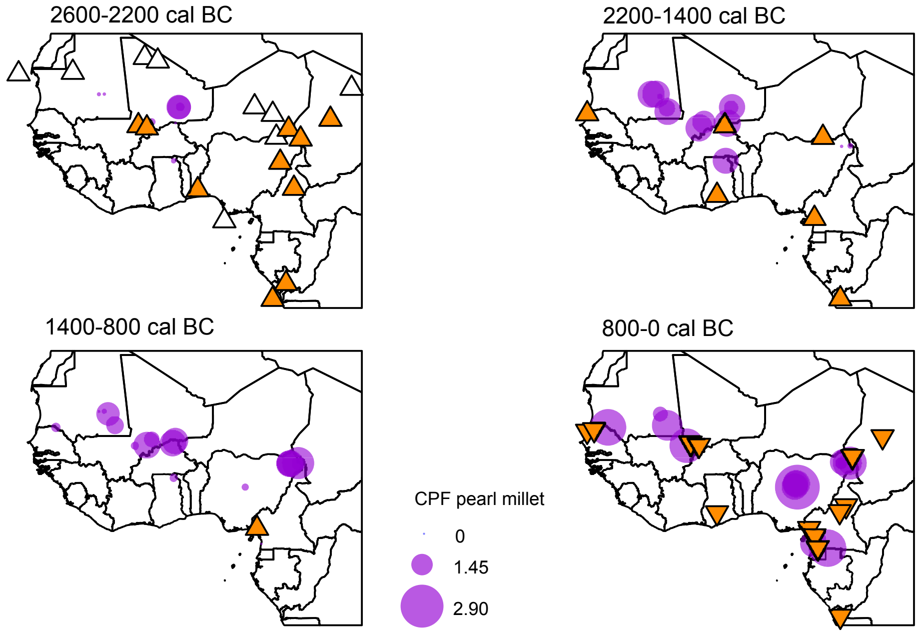


Fig. 6. Mapping of pearl millet CPFs, with contemporaneous transitions to dryer environmental conditions. The triangles represent the transitions to arid conditions in palaeoenvironmental records (see Table S2). On the 2600–2200 BC map, hollow triangles indicate drying events prior to 3000 BC. At sites with a two-step drying process, the second transition is signalled by triangles with their tip down. Transparency of symbols does not have any numeric meaning but only serves to distinguish the superimposed dots on the maps.

diffused initially through migratory-like dynamics involving one or several cultural traditions sharing common Saharan ancestors.

A deviating pattern can be observed for the development of early agriculture in the Chad Basin of north-eastern Nigeria. The southern Chad basin was gradually settled following the regression of the lake from around 2000 cal BC, allowing first the occupation of the Bama Deltaic Complex where the Gajiganna culture developed between ca. 1800 and 800 cal BC (Fig. 1; Breunig and Neumann, 2002; Klee et al., 2004). The Gajiganna phase I people (ca. 1800–1500 cal BC) were mobile pastoralists producing ceramics stylistically and technically different from those of the Niger Bend, with neither roulette decorations nor vegetal temper, the latter being an important characteristic of the ceramics associated with the appearance of agriculture in the Tilemsi valley (Manning et al., 2011). Gajiganna phase II pottery is characterized by organic temper and many plant imprints, including pearl millet, especially from phase IIb around 1200 cal BC (Klee et al., 2004). Towards the east, the Chad Lagoonal Complex (*firki* plains) was drained and occupied later, from the beginning of the first millennium cal BC, simultaneously with the appearance of both roulette decoration and pearl millet, especially at Kursakata (Fig. 1; Wiesmüller, 2001; Klee et al., 2000; Zach and Klee, 2003). The southern Chad Basin was therefore not settled first by agro-pastoralists arriving from the Niger Bend area, but rather by herders with distinct Saharan origins outside the core area of pearl millet domestication (see 3.3), possibly from northern Niger or Chad (Breunig and Neumann, 2002) or even from the eastern Sahara (Ozainne, 2013). The available data do not demonstrate whether the appearance of pearl millet during Gajiganna phase II reflects contacts with cultivators coming from the Niger Bend, excluding the adoption of roulette-decorated pottery, or with other groups originating directly from other regions in the core area of pearl millet domestication. The late settlement of the *firki* region by groups that had already acquired both roulette decorations and pearl millet could reflect either a rapid acculturation linked with the main expansion process described or a distinct peopling event remaining invisible with regard to the available data.

Some acculturation processes must have occurred at the forefront of the agriculture expansion system in the savannah from 2200 cal BC. Although we question the possibility of local agriculture in central Ghana (see 2.1), the Kintampo traditional ceramics at Boase (1800–1400 cal BC) comprise several northern components, including decorations made with rocked or impressed "cord-wrapped combs", although the use of these tools in the roulette technique is very rare (0.5–0.7%) (Watson, 2010). These low percentages tend to indicate some cultural borrowing resulting from contacts or trade with the Sahelo-Saharan pioneering front of agro-pastoralism. Such a model would also explain the unique occurrence of pearl millet at Boase.

These acculturation processes may have gained importance from ca. 1400 cal BC, as pearl millet began to spread more rapidly (Figs. 2, 3 and 5). The Gajiganna example previously described seems to support this idea. However, once again, we are aware that available data remain scarce and that further fundamental research is needed to confirm this point.

After 800 cal BC, cord-wrapped roulette decorations associated with the first expansion of agriculture quickly decreased in the Middle Niger area but gained importance eastwards, as they progressively reached the northern edges of Central Africa (Langlois, 2004; Livingstone-Smith, 2007). For instance, this trend is well recorded in the Dogon country (Mali), where cord-wrapped roulette impressions are clearly the dominant pottery decoration technique between 1800 and 400 cal BC before they decline and totally disappear during the first centuries cal AD (Huysecom et al., 2004; Ozainne, 2013; Mayor et al., 2014).

3.3. Climate-related cultural changes as mechanisms of agriculture expansion

Palaeoenvironmental data show that the change to dryer conditions during the Late Holocene in West Africa occurred unevenly. Only one main drying phase is observable in some regions of the Sahelo-Sudanian belt, but it is associated with some important spatio-temporal variability (Fig. 6; Table S2). On the other hand,

qualitative analysis of aridification evidence seems to confirm the quantitative method proposed by Lézine et al. (2011). Both approaches show that in the Late Holocene archives, two main phases of drying interrupted by a more humid period are frequently present (Figs. 5 and 6). This pattern is especially noticeable in the records of Lake Chad and Bar-el Ghazal (Maley, 1981, 2010; Servant, 1983) but also in the Guinean zone (Marret et al., 2006). This two-step drying process is also perceptible in the phytolith sequence of the Yamé valley in the Dogon country (Mali), which is associated with an accurate chronological framework (Eichhorn et al., 2010; Lespez et al., 2011; Garnier et al., 2013). A first opening of the vegetal landscapes occurred at the bottom of the valley between 2800 and 2200 cal BC, and a second one took place between 800 and 400 cal BC, including the transition from a dense Sudanian woodland to a wooded anthropic savannah and increasing colluvial processes (Garnier, 2013). Phytoliths also indicate an intermediate phase of vegetation closure at the bottom of the valley between 1300 and 800 cal BC, suggesting more humid conditions, despite the archaeological record pointing to increased human occupation of the immediate surroundings during the same interval (Ozainne et al., 2009; Ozainne, 2013).

The expansion of agriculture in West Africa cannot be considered a simple and uniform response to abrupt climatic change between ca. 2500 and 2000 cal BC. The trigger can be better explained through a more complex process following the desiccation of the Sahara, which itself involved considerable socio-economic transformations at some time between 4000 and 2500 cal BC. During this interval, the drying out of the Saharan water bodies was coupled with a reduction in plant diversity (Watrin et al., 2009; Lézine et al., 2011) and thus a decrease in wild grass resources exploited as pastures and through a system of selective gathering by Mid-Holocene Saharan pastoralists (Schulz, 1991; Neumann, 2005; Huysecom, 2012). Then, according to the resilience theory (Holling and Gunderson, 2002; Redman, 2005), populations probably entered a reorganization phase of their adaptive cycle and initiated another system to take advantage of the opportunities of new environmental conditions. The pastoralists most likely started exploiting more intensively the resources available around seasonal streams and ponds. The cultivation of pearl millet may have started and/or developed within such a framework. Yet, understanding the domestication of pearl millet requires further investigations and will not be discussed here.

The desiccation of the Sahara had an important cultural impact, which enabled a successful adaptation to the increasingly arid conditions of the Sahelo-Saharan zone and to the Sahelo-Sudanian landscapes that began to open after 3000 cal BC, a trend that probably intensified around 2000 cal BC. This allowed the first agro-pastoralists to expand quickly in more southern regions from around 2200 cal BC (Figs. 3, 5 and 6). These first farmers still had a partially mobile lifestyle and probably exploited plant resources of environments with extended water availability and thus specific habitats naturally favourable to pearl millet cultivation, which enabled the spread of this innovation somewhat independent of climatic constraints. This phenomenon could have enhanced the rapid expansion of agriculture through the 2nd millennium cal BC, during which farmers settled areas located in every part of the bioclimatic zone where pearl millet cultivation was possible (Figs. 3, 5 and 6). In addition, at least one group from agro-pastoralist populations probably conducted a seasonal transhumance, which was necessary because of the seasonal variation of grazing resources. Transhumance enabled new suitable territories to be explored and thus probably increased the rapidity of expansion southwards.

This important socio-economic mutation is visible through tangible changes in the material culture, one of the most remarkable being the increase in cord-based roulette pottery decorations. Although this technique probably arose during the Early Holocene in the central Sahara, it experienced a great development around the mid-3rd millennium cal BC along with the appearance of agriculture south of the Sahara. The broad spatio-temporal association between cord-roulette decorating techniques and domesticated pearl millet throughout the study period makes this stylistic feature a good material marker of the overall dynamics and reinforces the assumption that the expansion of agriculture may have had a mainly cultural mechanism, triggered by a change in environmental conditions in the Sahara during the Middle Holocene.

The return of more humid conditions in the western Sahel during the second millennium cal BC (Figs. 5 and 6) may have changed how agriculture expanded between ca. 1400 and 800 cal BC, which shows a more longitudinal pattern during this period (Fig. 6). However, the existing data do not reveal whether the appearance of domesticated pearl millet around Lake Chad is linked to an eastern expansion of agriculture from the Niger Bend or reflects the existence of another corridor from the central Sahara. Many palaeoenvironmental records indicate that landscapes in West and Central Africa experienced major changes from 800 cal BC, highlighting the onset of more arid conditions along the Sahel belt and in the southern forest areas (Fig. 6). Recent research points to important disturbance and opening of central African rainforests linked to the appearance of a marked seasonality after ca. 400 cal BC, probably related to a dramatic southwards shift of the Inter Tropical Convergence Zone (Ngomanda et al., 2009; Maley, 2010; Maley et al., 2012; Neumann et al., 2012a, b). During the first millennium cal BC, agriculture also developed specifically in humid environments of the Sahelo-Sudanian belt (Inland Niger Delta, Middle Senegal Valley, Lake Chad, Jos Plateau) while it was temporarily implanted in southern Cameroon (Fig. 6). After 800 cal BC, West African food production entered a new phase of development, which involved not only a likely intensification of pearl millet cultivation in favourable regions, as shown by the Lake Chad area data, but also a diversification of domestic plant species. In fact, in the Niger Inland Delta in Mali, the presence of domestic rice (*Oryza glaberrima*) is attested from 800 cal BC (Murray, 2004). In the same region, sorghum (*Sorghum bicolor*) is rather visible from the end of the 1st millennium BC, while fonio (*Digitaria exilis*) appears from 400 cal AD (McIntosh, 1995), although the latter has been mentioned in contexts dated around 800 cal BC (Takezawa and Cissé, 2004). In addition, mixed systems also developed, as shown by the combined production of pearl millet and cowpea (*Vigna unguiculata*) in Burkina Faso and Nigeria during the Iron Age period (Kahlheber and Neumann, 2007; Kahlheber et al., 2009).

Interestingly, this general scheme is consistent with a genetic study, which assumes a monophyletic origin for domestic pearl millet in an area comprised between the Inner Niger Delta and the Aïr Mountains (Oumar et al., 2008). Following the environmental changes between 4000 and 2500 cal BC, the expansion of agriculture out of this core area towards the Sahelo-Sudanian belt may thus have been carried through different but related cultural vectors with common origins in the central Sahara, the main one being particularly visible through the rise and spread of roulette-decorated pottery.

4. Conclusion

Spatio-temporal analysis of archaeological data suggests that the spread of agriculture in West Africa can broadly be explained by a combined climate-culture mechanism. The first agro-pastoralists adapted to the desiccation of the southern Sahara and developed new ways of exploiting resources by taking advantage of habitats

allowing both herding and pearl millet cultivation, which led to a rapid expansion of agriculture in savannahs after 2200 cal BC. Furthermore, cord-wrapped roulette-impressed pottery appears to be a good indicator of the pioneering advance of agro-pastoralist populations in Sub-Saharan regions. This cultural pattern strengthens the idea that the first cultivators were pastoralists with central Saharan origins. Our reconstruction of agriculture expansion from available archaeological data is also consistent with the assumption of a monophyletic origin of domestic pearl millet in a core area located between the Inner Niger Delta and the Aïr Mountains.

These results encourage further investigation of the Late Holocene period in West Africa, which appears to be a key study region for a better understanding of the relationship between environmental changes and socio-economic innovations related to the development and differentiation of food production. Our work points out that climate, peopling and cultural events are not necessarily tied by exclusive and negative causal links, although this kind of proposition is frequently found in the literature. It is of great importance to uncover more sequences enabling joint environmental and archaeological studies with a high chronological resolution. Although it is very difficult or impossible, due to current security problems, to schedule new field research in many relevant regions, we believe that modelling existing data is helpful in designing a more precise reconstruction of the cultural processes involved in the spread of early food production in Sub-Saharan West Africa. The development of such approaches is valuable for defining an enhanced theoretical framework, formulating new research questions and, eventually, preparing future fieldwork in appropriate areas.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.jas.2014.07.025.

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